BIOMASS AND BIOENERGY 32 (2008) 289–300

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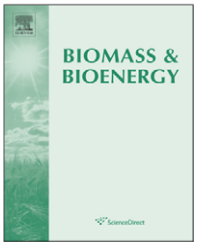

GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities

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ARTICLE INFO

Article history:
Received 15 March 2007
Received in revised form
12 October 2007
Accepted 18 October 2007
Available online 11 December 2007

Keywords:
GIS
Marginal delivery cost
Biomass allocation
Energy facilities location

ABSTRACT

This paper presents a GIS-based decision support system for selecting least-cost bioenergy locations when there is a significant variability in biomass farmgate price and when more than one bioenergy plant with a fixed capacity has to be placed in the region. The methodology tackles the resources competition problem between energy facilities through a location-allocation model based on least-cost biomass quantities. Whole system least delivery cost including intermediate bioenergy products is estimated. The methodology is based on a case study where forest wood residues (FWR) from final cuttings (FCs) are used to produce torrefied wood (TW) in two torrefaction plants (TUs) that supply a gasification unit (GU) in order to produce electricity. The provinces of Navarra, Bizkaia, Gipuzkoa, Alava, La Rioja, Cantabria and Burgos are assessed in order to find the best locations for settling down the TUs and the GU according to biomass availability, FWR and TW marginal delivery costs.

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1. Introduction

1.1. *Biomass spatial distribution and bioenergy facilities location*

Biomass to energy projects are highly geographically dependent and the plant's profitability can be strongly influenced by its location [1]. Commonly, biomass production and transportation account for a significant part of the whole bioenergy costs [2]. The key element is to obtain sufficient biomass quantities in order to satisfy the energy plant demand at the least cost [3].

The problem of choosing the best locations for energy facilities is commonly assessed without considering the sites competition for the biomass resources. GIS-based applications have been used for biomass-availability estimations [2–14] and for deciding the sites of only one facility [1,14–24] without assessing the sites competition for the raw material. Biomass quantities and their related production and transportation costs over a defined region are assessed. The marginal price surface methodology is the commonly used approach. So, when the number of supply and demand points is very large, all points in the territory are assessed both as supply and demand locations, and so the energy units are placed in the areas where the marginal delivery price is the lowest. The biomass farmgate price varies only as a function of the present biomass quantity in the parcel and the decision is strongly influenced by transportation costs.

On the other hand, the farmgate price of the available biomass has a strong spatial variability when considering multi-sources of biomass, rotation periods, production technologies and human accessibility to the biomass resources. So, it can happen that the delivery price of biomass quantities near the facility is higher than that of more distant ones.

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doi:10.1016/j.biombioe.2007.10.008

Nomenclature

BD	delivered biomass (d.m. t yr^{-1})
d.m.	dry matter
D_{TU}	biomass demand at TU (d.m. kt yr^{-1})
FC	final cuttings
FL	forest location
FSF	forest storing facility representing the central location of FL (*i*)
FWR	forest wood residues
GU	gasification unit
i	point element representing FL (100 ha)
j	nearest road junction to FL
k	TU candidate location in road junction
t	tonne
TU	torrefaction unit
TW	torrefied wood

In some cases, the problem consists of choosing simultaneously the location of more than one energy unit. In this context, the maximum radius approach is often used while avoiding overlap of collection areas. A maximum distance from the energy unit (placed in the centroid of the collecting area) is established and all the biomass quantities inside this radius are supplied to the facility. Under this approach, biomass supply curves are designed and the plant's capacity is defined as a function of the marginal delivery cost of the biomass. To this end, biomass delivery cost is lower when the plant's capacity is small and vice versa, as transport costs are a significant component of the supply costs.

1.2. *The location-allocation problem*

Finding the best locations for several energy units taking into account the sites competition for resources is not straightforward. When the raw material in the region is scarce, the energy facilities have to compete for the biomass resources in order to meet their own demand. Collection areas may overlap and biomass amounts supplied to one unit will not be available for the other one. This leads to an interactive location-allocation problem. Only a few authors have formally treated this problem [3,18].

Linear programming was applied in order to minimize transportation costs to the candidate units [8,19]. Other authors used ArcInfo allocation function [17]. Farmgate price variability is rarely considered in the decision of the energy locations. Other approaches assigned biomass quantities to the facility that pays the maximum farmgate price [3] or proceeded by excluding biomass quantities allocated to the first unit to assess the biomass to be delivered to the second one [15,16]. In this case, best sites are selected one by one but not simultaneously. So, the first facility will always pay a lower price for the biomass than the second one. Under the maximum radius approach, exceeding biomass in a collection area was allocated to another facility [18].

This paper presents a new approach for selecting least cost bioenergy locations when there is a significant variability in biomass farmgate price and when more than one bioenergy plant with a fixed capacity have to be placed in the region. The methodology addressed the resources competition problem between energy facilities, as well as the whole system delivery cost reduction when intermediate bioenergy products are present.

Section 2 describes the methodological approach concerning how to estimate biomass availability for energy use, how to calculate the different cost components and how to decide where to locate the energy facilities based on least-cost options. The methodology is based on a case study where forest wood residues (FWRs) from final cuttings are used to produce torrefied wood (TW) in two torrefaction plants (TUs) that will supply a gasification unit (GU) in order to produce electricity. Section 3 presents the application of the methodology in the case study. The provinces of Navarra, Bizkaia, Gipuzkoa, Alava, La Rioja, Cantabria and Burgos were assessed in order to find the best locations for settling down the TUs and the GU, taking into account the biomass availability, FWR and TW marginal delivery costs. Results are presented and, finally, the extent to which the proposed methodology is effective in solving the interactive location-allocation problem is discussed.

2. Methodology

2.1. *Model overview*

The proposed model uses a least-cost approach to allocate biomass quantities between predefined candidate site combinations to find the best set of locations for the energy units.

Two torrefaction units with a processing unit capacity of 42 d.m. kt yr^{-1} of dried forest wood residues were planned to be constructed and operated in northern Spain for electricity production through gasification of TW. A total demand of 84 d.m. kt yr^{-1} of FWR was required to satisfy the TU's biomass demand. The produced TW will supply a gasifier that serves a 22 MWe combined heat and power generation plant connected to the national electricity grid.

For the case study, nine candidate sites were pre-selected based on accessibility to water resources, connectivity to the electricity grid, availability of industrial infrastructure, terrain cost and policy incentives for bioenergy production. Consequently, the final decision was taken based on the least logistic cost for meeting the required TW demand (Fig. 1). Dried forest wood residues from final cuttings were allocated to each combination of two TU's potential sites to define the best set of locations. The location-allocation problem was treated using a GIS-based approach (Fig. 2). A georeferenced database was created to evaluate the spatial distribution of the biomass resources, the farmgate price variability, the delivered biomass to each TU and the bioenergy facilities

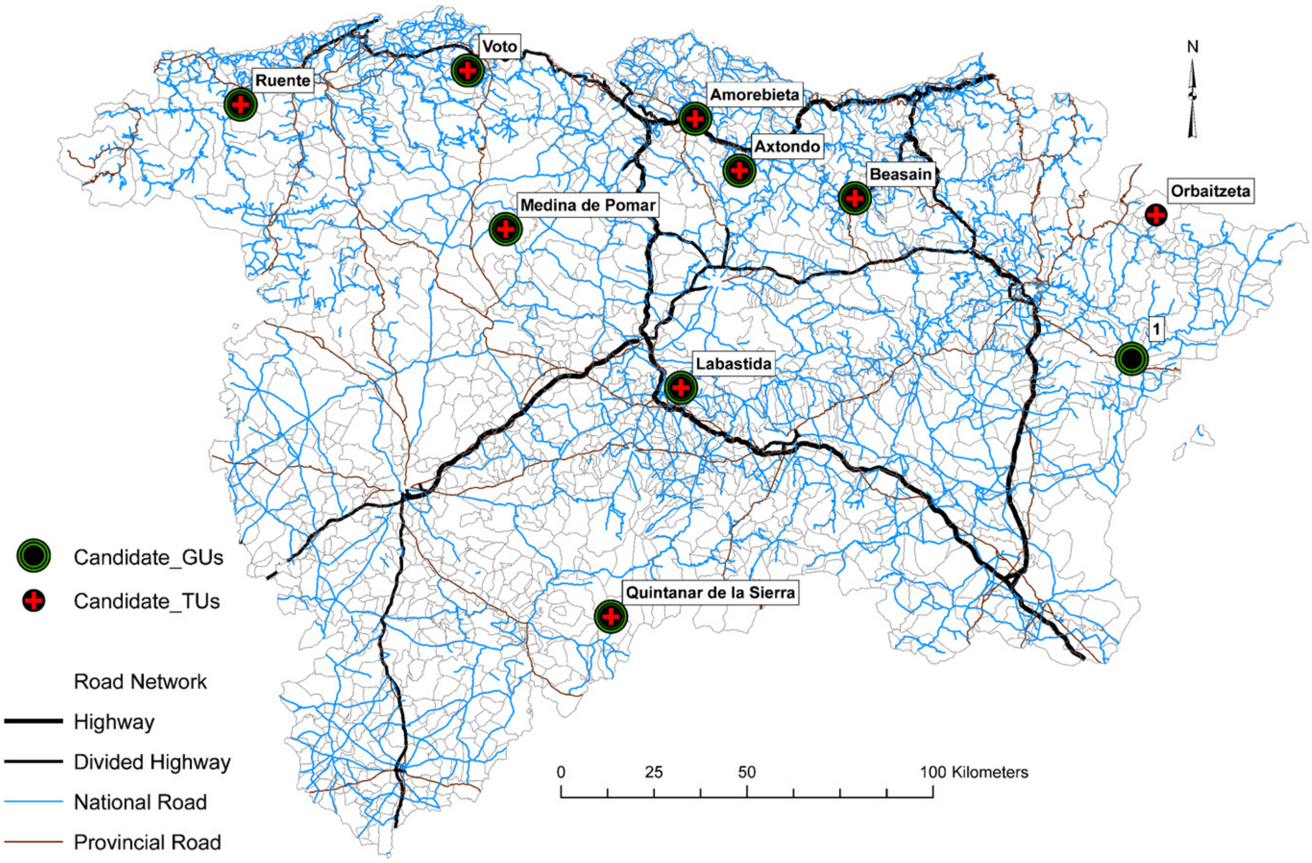

Fig. 1 – Candidate sites locations and transportation network.

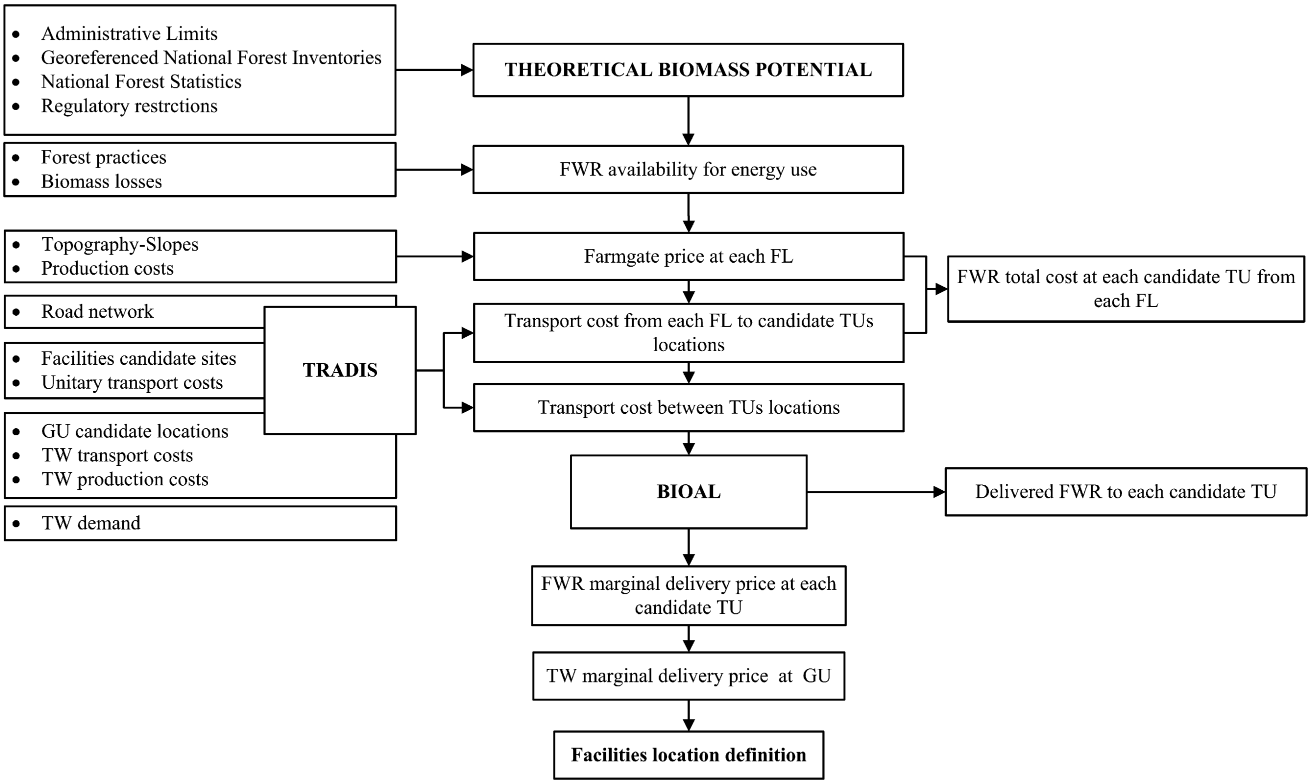
Administrative Limits
Georeferenced National Forest Inventories
National Forest Statistics
Regulatory restrctions
THEORETICAL BIOMASS POTENTIAL
Forest practices
Biomass losses
FWR availability for energy use
Topography-Slopes
Production costs
Farmgate price at each FL
FWR total cost at each candidate TU from each FL
Road network
Facilities candidate sites
Unitary transport costs
TRADIS
Transport cost from each FL to candidate TUs locations
Transport cost between TUs locations
GU candidate locations
TW transport costs
TW production costs
TW demand
BIOAL
Delivered FWR to each candidate TU
FWR marginal delivery price at each candidate TU
TW marginal delivery price at GU
Facilities location definition

Fig. 2 – Methodology overview.

location. Administrative limits were used to place and visualize the whole system.

Georeferenced forest land was obtained from the National Forest Inventories as data points (forest locations (FLs)) representing 1 km^2. Biomass availability for energy use was estimated considering protected areas, soil protection and biomass losses. Then production costs were assigned to each FL based on human accessibility, production technology, tree species and forest development stage. Transport costs from FL to TU candidate sites and between energy facilities were assessed creating a geometric road network. A least-cost algorithm to determine the shortest pathway was developed at that end.

Then, using the BIOAL algorithm, biomass quantities were allocated to each TU's combination and TW marginal delivery price was then estimated. The TU's combination with the least TW marginal delivery price was selected as the best set of locations.

2.2. *Estimation of biomass amount availability for energy use*

Final cuttings produce most of the wood residues generated by a forest plantation during its rotation period [25] and represent the most economical and technical biomass fraction to be used in a bioenergy system. The theoretical biomass potential was defined as the quantity (d.m. kt yr^{-1}) of forest wood residues produced from final cuttings (FCs) of non-protected dense-wooded forest from exploitable tree species in the whole region. It is a function of forest type, protected areas and exploited tree species. The biomass production is assumed to be constant along the year, i.e. there is no seasonal variation.

Biomass availability is estimated based on National Forest Statistics [26] and National Forest inventories. The 2006 version of the inventories was used in Cantabria, La Rioja and Navarra. Nevertheless, the 1996 version was used for the remaining provinces as the new version was not available. Each georeferenced data point from the inventories contains information regarding the three main species present in the parcel (name, forest development stage, percentage covered of the parcel). The total average (period 1996–2003) volume of commercial wood cut from each tree species in each province was obtained from statistics and assigned to the forest location. Stem volume production represents the real annual wood volume available at each FL. The Spanish National Forest Inventory divides forest development into four stages. Only timber stage parcels, except from short rotation species, are considered as it is assumed that those parcels are the ones to be exploited within the lifetime period of the energy facilities. For *Eucalyptus globulus* and *Populus nigra*, all forest development stages were considered. For *Pinus radiata* also the pole was taken into account.

FCs wood stem volume for each tree species and province was divided by the number of parcels containing the selected forest development stages, and assigned to the georeferenced points (FL) where those combinations (species-forest development stage) were present. FCs are assumed to be stable over time and biomass availability for other uses was assumed to be provided by pruning, first and commercial thinnings.

Then, biomass expansion factors (BEFs) available for the southern part of Spain [27] were used to convert stem volume production into annual biomass quantities at the parcel level. Only branches and foliar biomass were considered.

Finally, dried forest wood residues available at each FL for energy use were estimated. Useful biomass potential was defined as the total dried biomass quantity (d.m. kt yr^{-1}) from the exploited species, in their specific forest development stage and location, that can be technically and economically harvested and used for energy purposes. Soil protection practices and biomass losses [28] during supply chain were considered when estimating the available biomass quantities. Losses due to handling, storage and transportation of chips or TW are not included.

2.3. *Farmgate price calculation*

Production costs present significant variability as a function of tree species, slopes, parcel quality, proximity of forest roads, forest development stage, forest treatment, type of useful biomass and non-productive time. Farmgate price was estimated considering the biomass bundling system with chipping at the terminal, as it is the most efficient system for chips production from logging residues [25,29]. The logistic structure of the bioenergy system was modeled and costs were estimated from biomass harvesting in forests to TW transport to the gasification unit. Collection, haulage, packing and bale storage were summed up to obtain the biomass farmgate price. The biomass farmgate price is the price that an energy facility has to pay to a forest supplier for the biomass at the forest parcel, not including transport [21]. For this work it includes all production costs from residues collection, packing, storing in forest and haulage to forest storing facilities (FSFs). Forest wood residues were assumed to be stocked at a FSF available at each forest location. Human accessibility to biomass sources was assessed based on terrain slopes, through a Digital Terrain Model of the region.

Biomass farmgate price was determined for each parcel as an average of the specific production cost for each tree species. Different costs were assigned in a function of tree

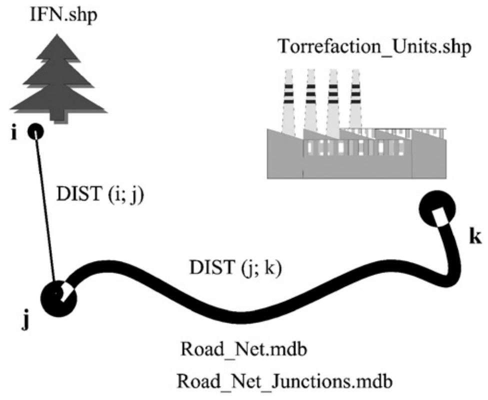

Fig. 3 – Shortest path calculation.

species, slope and forest development stage. These characteristics define different harvesting, haulage and packing methods for each considered source.

Biomass production is considered an associated activity to forest management, and many of the machinery and human resources are used by both activities. Cost of biomass storage

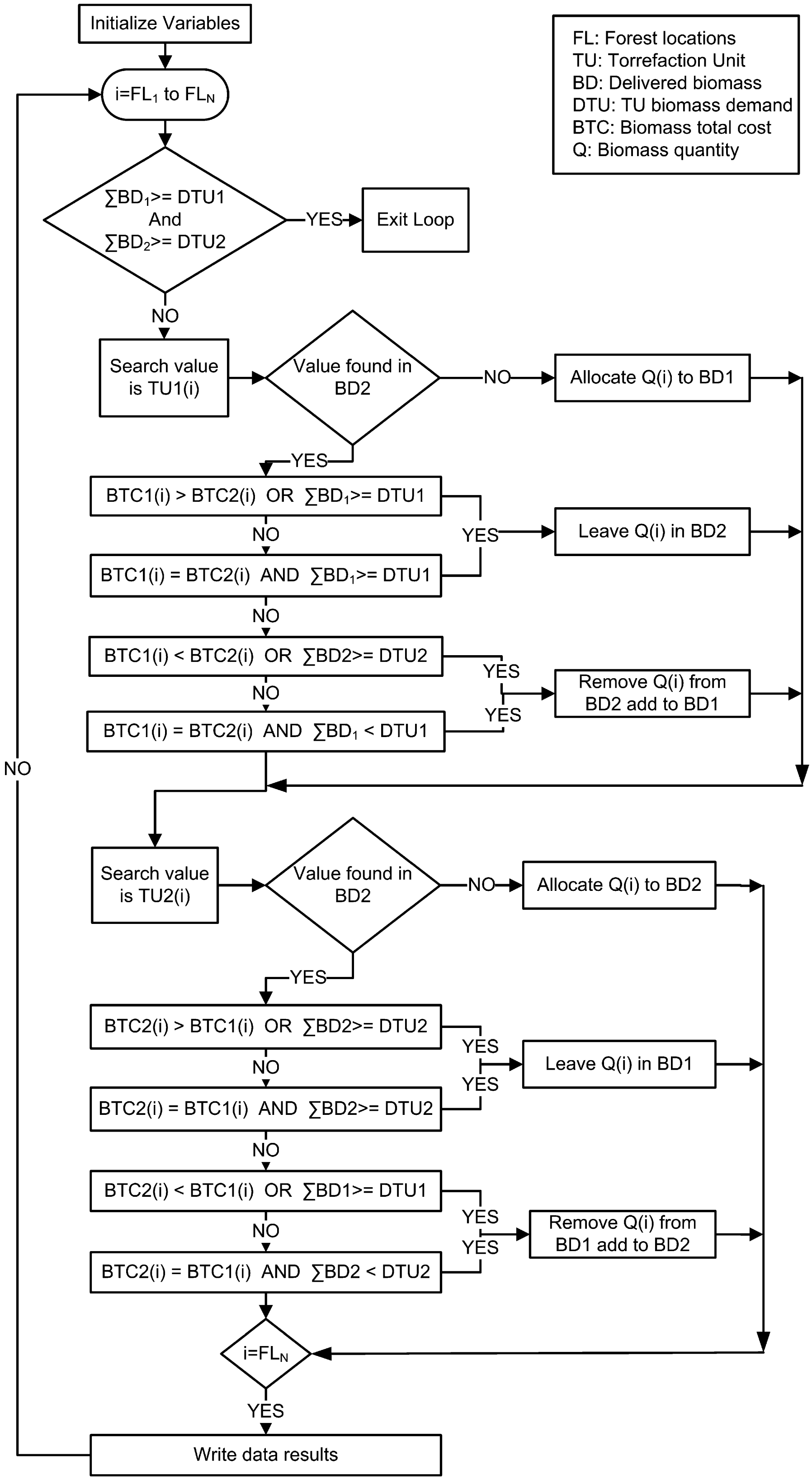

Fig. 4 – BIOAL algorithm.

in forest was considered as included in the total farmgate price. For this case, the storage costs are equal for all forest locations and so they will not influence the location decision.

Even though harvesting operations are a main step and a key issue in biomass production, the associated costs were not considered as they were assumed to be part of forest management activity.

Results were presented as thematic maps of farmgate price ranges for the study area, aggregated by municipality.

2.4. *Biomass transport and total cost*

The logging residues transport cost for each of the identified plants was estimated using the road network. A geometric network was created in order to find the most efficient way to transport the bales from FSF to the TUs. Road network junctions connecting the different road types were created. TUs at each specific selected location were placed in the junctions. Then, the distance between the forest location and the TUs was calculated applying the shortest path methodology [22]. For this purpose a simplified Dijkstra algorithm [30] programmed in Visual Basic was applied (Fig. 3).

Transportation from each FSF to each TU was estimated considering forest and main (highway) roads. Weights were assigned to each road type to consider the speed variation and the toll in divided highways. Finally, the total least-cost path was obtained by summing up the straight-line distance—*DIST* (*i*,*j*)—from FL (*i*) to its nearest road network junction (*j*), the corrected road section across the network between the nearest junction to the FL (*j*) and the TU junction (*k*). Straight-line distances (*i*,*j*) were divided into three distance ranges, and three different transport costs were assigned according to distance. An average transport cost to the TU was calculated for each FL considering the bulk density of the main species present in the parcel.

Finally, the biomass total cost of supplying biomass from each FL (*i*) to a specified TU (*k*) is obtained by summing up biomass farmgate price at the parcel and transportation costs to the TU.

2.5. *Search of best locations for bioenergy facilities*

Best locations were defined based on the marginal delivery cost of supplying TW to the GU. This cost is estimated as the sum of the biomass marginal delivery cost, the bale chipping cost, the bale drying cost, the TW production cost, the TW storing cost and the TU transport cost to the GU.

Once we have determined the biomass total cost from each FL to the TU, we have to decide which FLs will supply each of the TUs. The location-allocation problem was solved using the BIOAL algorithm developed for this purpose (Fig. 4). The algorithm was programmed in Visual Basic and requires between 2 and 15 min to be solved depending on the biomass demand to be allocated. The program allows

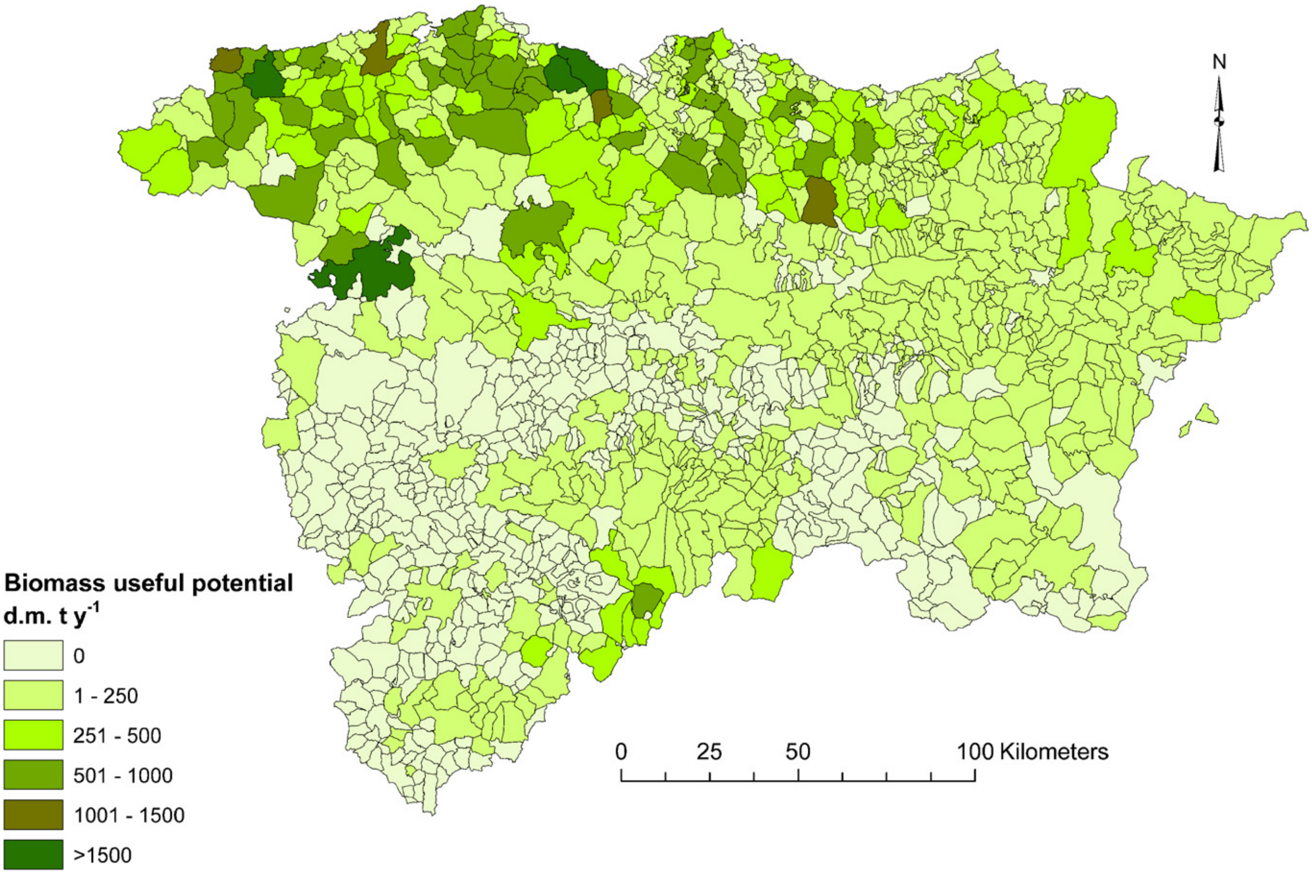

Fig. 5 – Biomass useful potential.

allocating least-cost biomass quantities between two energy facilities until the specified biomass demand (D_{TU}) is reached.

At this end, 36 site combinations of two sites, resulting from the interaction between the nine candidate locations, were evaluated. The biomass marginal delivery cost for each TU was estimated.

The biomass total costs at each FL are sorted in ascending order for each TU. Using each couple of TUs (TU1 and TU2), the least biomass total cost was selected to reach the facility demand, ensuring that the FLs are unique to each TU. Duplication between TUs is avoided by placing the FLs into one or the other TU depending on certain conditions. If the biomass total cost is less for TU1 then the biomass is allocated to this TU. If both sites compete for the biomass quantity at an FL and the cost is the same, biomass is given to the site which has the least allocated biomass quantity (DB1 or DB2). Once one site reaches the required biomass, the biomass is automatically given to the other site until it also reaches its demand. Then, the biomass marginal delivery cost for each combination was obtained.

Then TW production costs are added and transportation cost from the TU to each of the GU potential site locations is estimated. For this purpose the same methodology is used, obtaining the TW marginal delivery cost from the TU to the GU. In this case, 71 combinations of two TUs and one GU were assessed, resulting from the interaction of the nine TUs and nine GU candidate sites.

TW production costs include those for bale chipping, chip drying, TW production process, and storing of TW. TW is transported from the TUs to the GU by highway or main roads, as they are placed in road network junctions. In this case study, chipping, drying, TW production and storage costs are the same for all TUs.

Finally, TUs' combination with the least TW marginal delivery cost was selected as the best locations for the energy facilities.

3. Results and discussion

3.1. Biomass availability and delivery costs

Biomass theoretical potential was estimated in 243 d.m. kt yr^{-1} of FWR. However, the biomass availability for energy use was calculated in 112 d.m. kt yr^{-1} of dried forest wood residues as the useful potential accounts for soil protection constraints and biomass losses during the process. This quantity is enough to supply the two TUs.

Biomass resources present a significant spatial distribution (Fig. 5). Higher amounts of FWR are located in the north-west part of the territory (Cantabria, Vizcaya, Alava, Gipuzkoa and

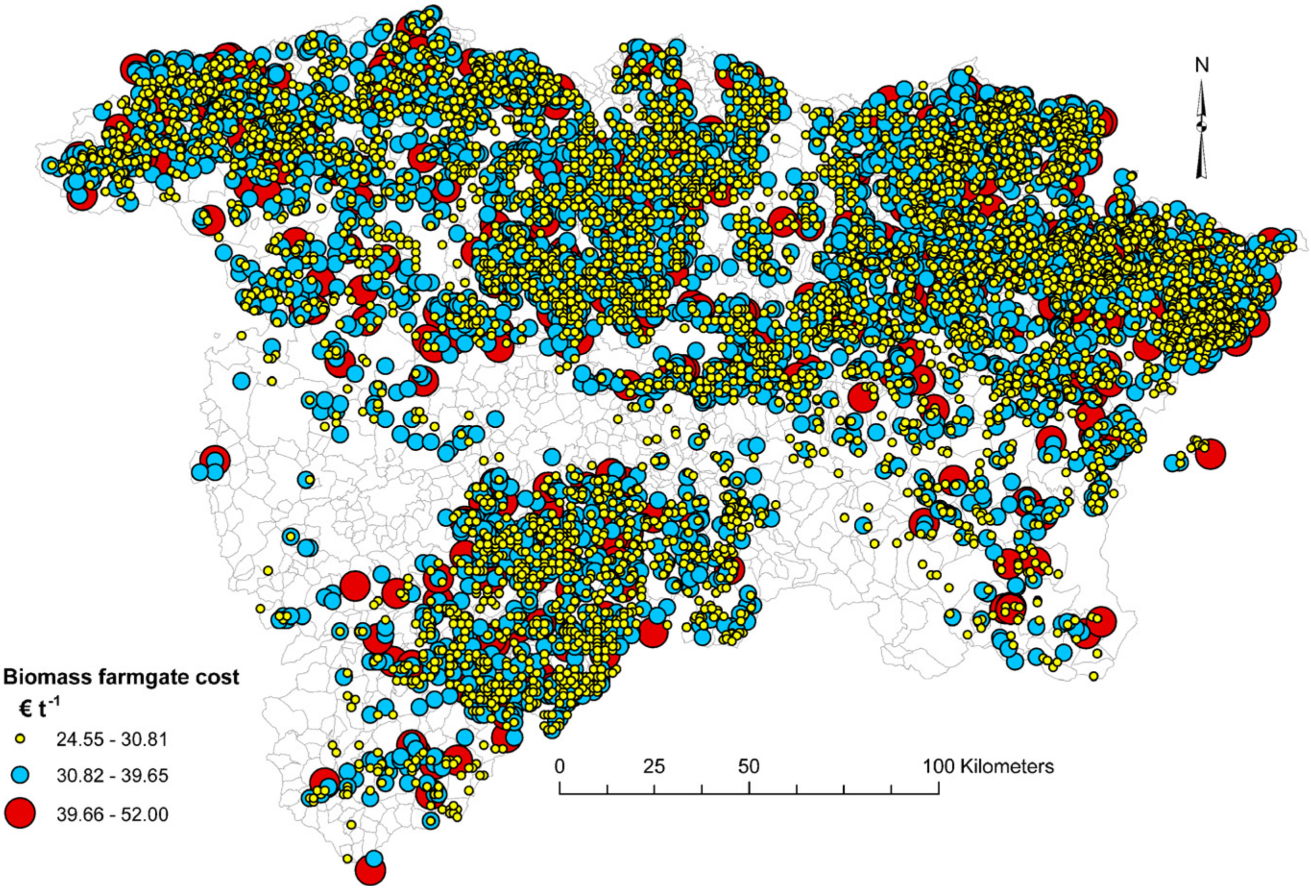

Fig. 6 – Biomass farmgate cost spatial variability.

north of Burgos), as a consequence of the high concentration of short rotation species, mainly *E. globulus* and *P. radiata*. In the south (eastern part of Burgos and western part of La Rioja), another high biomass density zone is observed. Thus, these are the most suitable zones for placing the energy facilities under a resources availability criterion.

Biomass farmgate price represents approximately 69% of the total biomass cost. Spatial distribution of biomass farmgate price for the whole region is shown in Fig. 6. Significant spatial variation and cost differences are observed. Biomass farmgate price ranges from as low as 24.6 to 52 € t^{-1}. This difference is due to the variability in production methods, forest development stages and tree species in each parcel.

Transport costs of forest residues are divided into forest road transport and normal road (national/provincial road, highway, divided highway) transport. In the first case, transport costs represent around 8% of the total biomass cost, as transport distances are short (2 km in average). On the other hand, normal road transport costs represent 24% of the total average biomass cost for the region. Delivered biomass transport costs for the TU located in Axtondo are shown in Fig. 7. Obviously, transport costs increase with distance to FL.

TW transport costs range from 14 € t^{-1} for the combination Amorebieta–Axtondo (traveling factor: 23 km) to 188 € t^{-1} for the combination Orbaitzeta–Ruente (traveling factor: 314 km). Other least transport cost combinations are Beasain–Axtondo (24 € t^{-1}, 41 km), Voto–Medina de Pomar (43 € t^{-1}, 73 km), Amorebieta–Voto (45 € t^{-1}, 76 km) and Ruente–Voto (45 € t^{-1}, 75 km). Transport costs are linearly linked to transport distances between gasification units.

3.2. *Best locations for bioenergy facilities*

The 10 best combinations of two TW facilities are presented in Table 1 based on the least TW marginal delivery cost.

The best candidate sites for the two TUs are Amorebieta and Axtondo, with an average TW marginal delivery cost of 106.77 € t^{-1}. Other suitable combinations are Beasain–Axtondo (106.90 € t^{-1}), Amorebieta–Beasain (112.13 € t^{-1}) and Voto–Medina de Pomar (118.76 € t^{-1}).

The biomass to be delivered to each TU for the best combination is geographically represented in Fig. 8. Note that for the best combinations the GU is placed in one of the TU locations, as transport costs are reduced.

Similar to other methodologies [16,22], a significant spatial variation in biomass marginal delivery cost between candidate sites location was found. A difference of 16 € t^{-1} was obtained between the best and worst combination. However, in our method, this is mainly due to the allocation procedure that considers not only transport costs but also farmgate cost variability in space. As no maximum radius approach was used, this allows satisfying the biomass demand partly with least farmgate price biomass quantities from more remote areas. Low biomass farmgate prices are then compensated

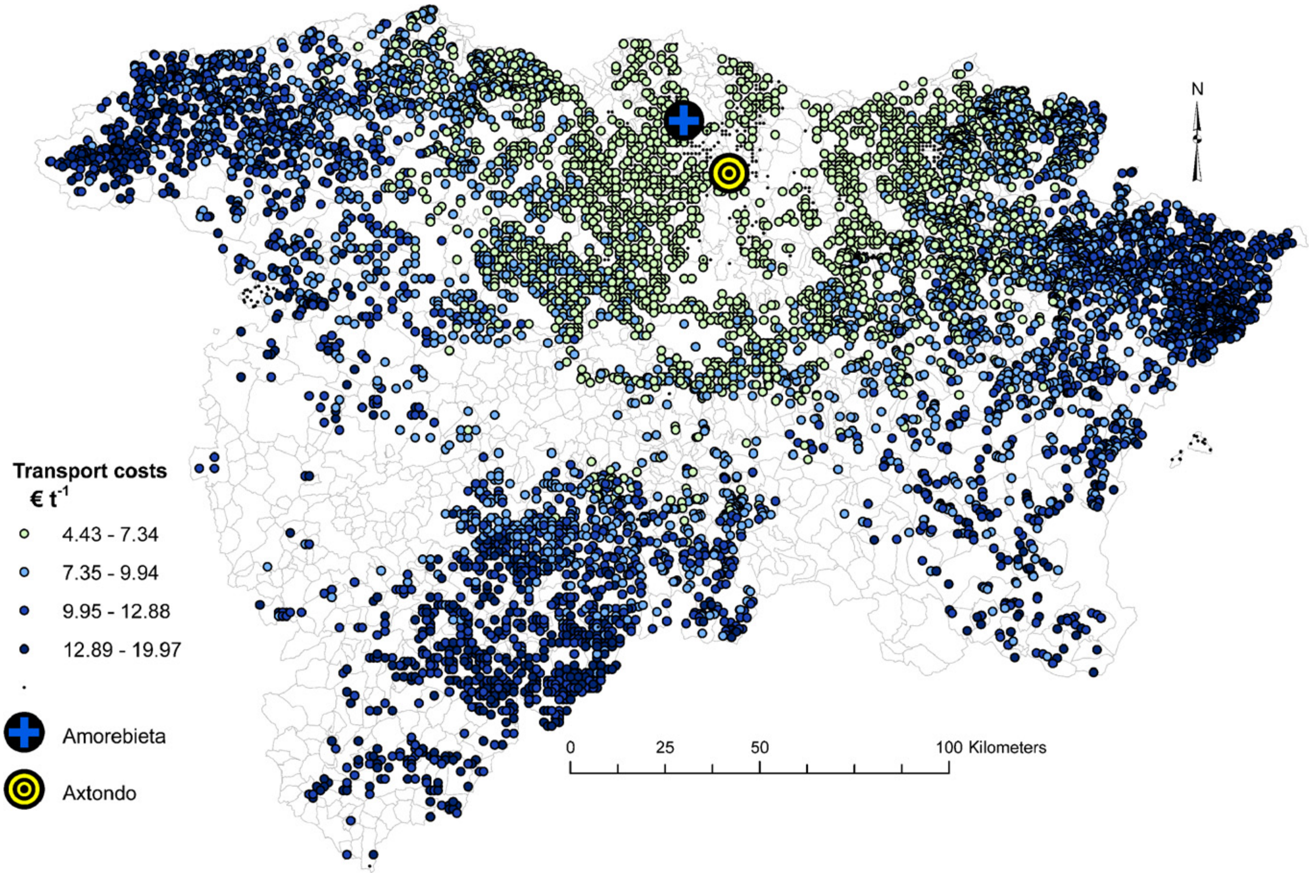

Fig. 7 – Biomass transport cost.

Table 1 – Forest wood residues and torrefied wood delivery costs for best sites combination

TU1-GU	TU2	Forest wood residues				Torrefied wood						
		Marginal delivery cost to TU1 €t^{-1}	Marginal delivery cost to TU2 €t^{-1}	Average marginal delivery cost €t^{-1}	Chipping cost €t^{-1}	Production cost €t^{-1}	Storing cost €t^{-1}	Transport cost from TU1 to GU €t^{-1}	Transport cost from TU2 to GU €t^{-1}	Total delivery cost from TU1 €t^{-1}	Total delivery cost from TU2 €t^{-1}	Average total delivery cost €t^{-1}
Amorebieta	Axtondo	48.59	42.59	45.59	2.5	47	1.7	0	14.05	99.74	113.79	**106.77**
Beasain	Axtondo	43.24	43.72	43.48	2.5	47	1.7	0	24.53	94.39	119.40	106.90
Amorebieta	Beasain	43.66	42.93	43.30	2.5	47	1.7	0	35.38	94.81	129.45	112.13
Voto	Medina de Pomar	48.56	42.95	45.76	2.5	47	1.7	0	43.71	99.71	137.82	118.76
Amorebieta	Medina de Pomar	42.91	44.93	43.92	2.5	47	1.7	0	49.16	94.06	145.23	119.65
Labastida	Axtondo	44.15	42.46	43.31	2.5	47	1.7	0	53.07	95.30	146.68	120.99
Amorebieta	Labastida	43.22	43.06	43.14	2.5	47	1.7	0	56.46	94.37	150.67	122.52
Axtondo	Medina de Pomar	42.78	43.98	43.38	2.5	47	1.7	0	58.40	93.93	153.53	123.73
Beasain	Labastida	42.09	43.06	42.57	2.5	47	1.7	0	62.49	93.24	156.70	124.97
Labastida	Medina de Pomar	41.81	66.10	53.96	2.5	47	1.7	0	46.94	92.96	164.19	128.58

with higher transportation costs. In consequence, biomass marginal delivery costs result from the combination of the optimal farm-gate and transport cost allocated to each TU.

The maximum radius approach may lead to select FL that are not the least cost in the region, as biomass has to be collected within a predefined and restricted area (collection area). On the other hand, even though biomass farmgate price in remote locations is as low as it is economically justified that it supplies the TU (transport costs are compensated by the low farmgate price), this may not be operationally possible or desired, particularly in cases where the biomass availability in remote FL is low. In conclusion, the approach leads to the least-cost solution, but with risks of being not realistic.

The optimal solution results from the combination of biomass marginal delivery costs to the TUs and TW transport cost from the TUs to the GU. Actually, the candidate sites with the least-cost biomass marginal delivery cost do not correspond with the optimal TU locations. This highlights the influence of TW transport distance between facilities, and its related cost. As expected, transport costs increase with distance from demand point to supply points and between energy units. Combination 16 (Amorebieta–Axtondo) is the best combination for placing the TUs, while combination 29 (Quintanar de la Sierra–Voto) presents the least-cost biomass marginal delivery cost. This result shows the importance of developing a new approach for analyzing facilities location under competition.

The BIOAL algorithm allocates biomass quantities with equal cost to the TU with the less allocated biomass amount. This has led to find some FLs spatially located in the Axtondo supplying area, but that are allocated to the Amorebieta TU. Even though, for this case study, only a few minutes are needed to solve the algorithm, it is true that this time can be significantly increased when searching for non-predefined candidate sites.

The model is applicable when candidate sites are predefined. In case of searching locations over the whole territory, suitable constraints should be added to take into account the criteria used to pre-select the candidate locations. Also, the model has assumed the forest managers' willingness to supply the required biomass. No political restrictions were present in the studied area. As this situation can change in the future, other constraints may be included.

Although total biomass cost in some FL is low, the available biomass quantity may not justify the fact that it supplies the TU. Biomass total cost is dependent on the biomass quantity available in the parcel. A suitable factor to integrate this aspect should be developed to evaluate the effect of biomass quantities at FL level in the marginal delivery cost. Due to lack of data, this parameter was not considered in the present model.

3.3. *Sensitivity analysis*

In this case study, torrefaction units use a significant portion of the biomass available in the region (84 of 112 d.m. kt yr^{-1} of dried FWR) as a fixed capacity was set. In order to evaluate the effect of facilities demand in biomass marginal delivery cost, alternative TU capacities were assessed (Fig. 9). A small unit

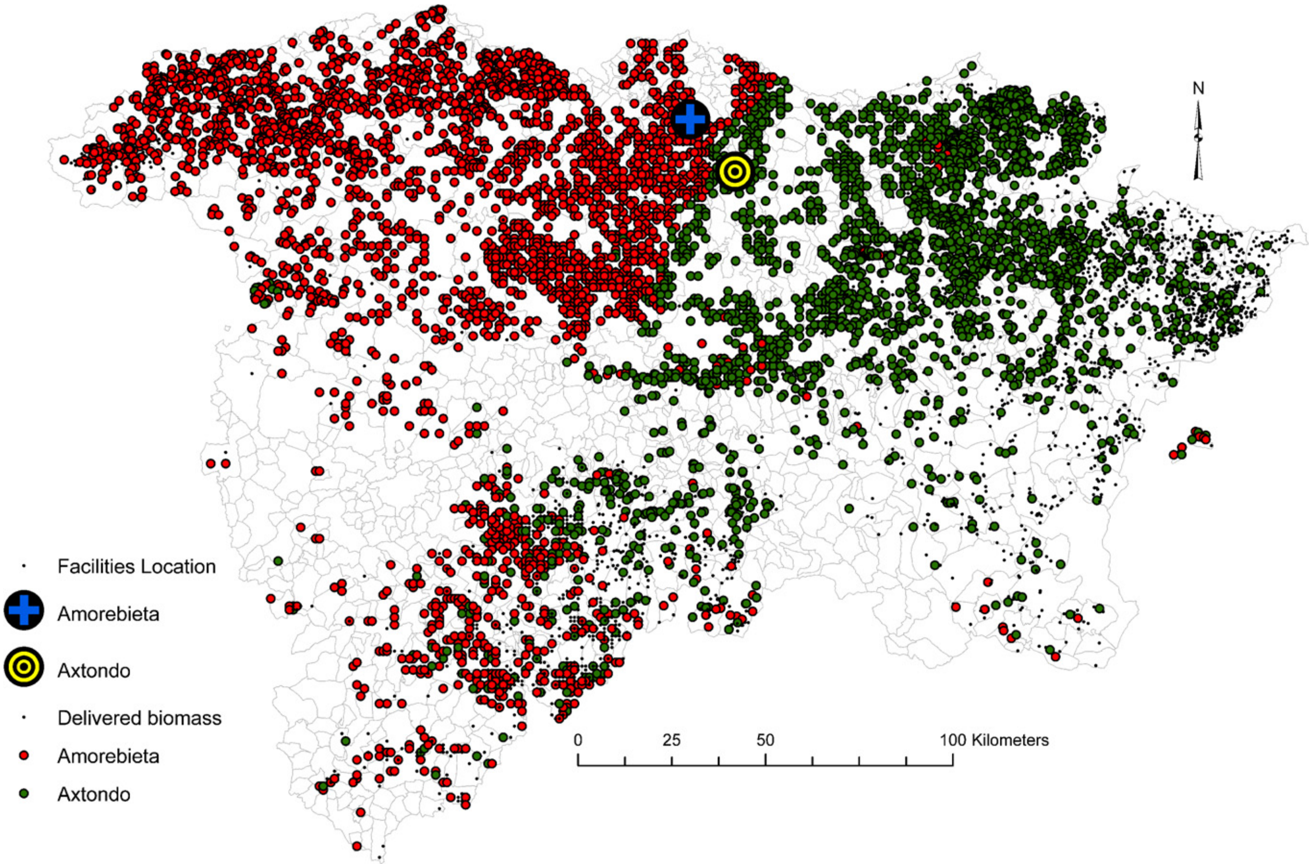

Fig. 8 – Spatial distribution of delivered biomass to optimal TU locations.

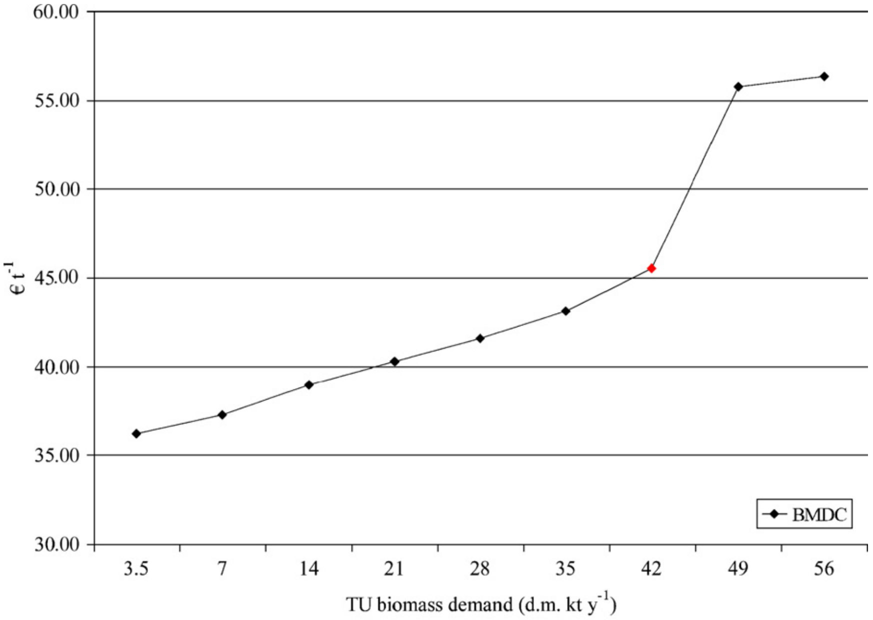

Fig. 9 – Biomass marginal delivery cost variation in function of TU biomass demand.

size should lead to lower biomass costs as transport distances are decreased. But, when biomass farmgate price is low in remote regions, transport costs are compensated with the least farmgate prices and no changes in facilities location are obtained. The same sites were found as the least-costs options independently of facilities demand. On the other hand, biomass marginal delivery cost increases gradually with increasing demand.

The system is economically viable up to two energy units of 42 d.m. kt of logging residues per year. When 49 or 56 d.m. kt units are assumed, biomass marginal delivery costs are extremely high. This can be explained by the fact that biomass maximum availability is reached and the units are supplied with small biomass quantities from remote areas with high farmgate prices. In conclusion, the chosen capacity is the optimal one, considering scale economy.

Biomass availability and facilities location were subjected to a boundary effect. Available biomass in neighbor regions was not considered. In consequence, candidate sites near the limits of the territory may fall in higher marginal biomass delivery costs that do not reflect the real situation.

As also stated by other authors [2,17,22] GIS limitations for data processing, biomass estimation methods and National Forest Inventories structure have led to increased uncertainty in the final results. Biomass potential was estimated applying biomass expansion factors of the Spanish southern region as no data were available for the northern region. However, the BEFs are related to climate, soil conditions and tree species. The latter are specific for each region. The forest inventory did not provide a geo-referenced database of tree species diameter to allow application of allometric equations, a method that is more accurate for these estimations.

4. Conclusions

When assessing simultaneous potential locations for energy facilities the location–allocation problem has to be solved in order to tackle resources competition between facilities. A GIS-based approach combined with a biomass allocation algorithm is effective for selecting suitable energy facilities location. Addressing the problem through a convenient approach is fundamental to define facilities location as the optimal sites can vary in function of resources competition.

The quantity and heterogeneity of the input data and the need for a structured analysis of the information make essential the need of integrated tools to assess the problem. Further efforts have to be done to integrate software tools and data processing. The developed approach allows allocation of biomass quantities in a least-cost way and select best energy facilities locations based on marginal delivery costs.

Nevertheless, other models of the logistic structure are being investigated, considering not only marginal delivery cost minimization but also environmental and social constraints.

Acknowledgments

We acknowledge Alanna Minogue and Holger Heisig for programming the BIOAL and the shortest path algorithms, respectively, and for their support in managing GIS and other software.

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